DOCUMENT RESUME

ED 186 801 CG 014 368

AUTHOR Greeno, James G.
TITLE Psychology of Learning, 1960-1980: One Participant's Observations. Technical Report Number 5.
INSTITUTION Pittsburgh Univ., Pa. Learning Research and Development Center.
SPONS AGENCY National Inst. of Education (DHEW), Washington, D.C.; Office of Naval Research, Washington, D.C. Psychological Sciences Div.
PUB DATE 25 Feb 80
CONTRACT N00014-78-C-0022
NOTE 66p.

EDRS PRICE MF01/PC03 Plus Postage.
DESCRIPTORS *Behavior Patterns; History; *Knowledge Level; Learning Processes; *Learning Theories; *Memory; *Models; *Psychology; State of the Art Reviews

ABSTRACT

By 1960 there was a strongly developed theory of learning in which learning was considered as change of behavior. Neobehaviorist theories and then formal stochastic models analyzed processes in which probabilities of responses are altered. In the 1960's, analysis of learning as a discrete change between states of knowledge or stages of processing that differ in qualitative characteristics began; stochastic models were used to represent these states and stages. In addition, the processes and structure of human memory were studied in detail. In the 1970's, detailed analyses of the organization of knowledge for understanding language and solving problems developed, using programming languages as formalisms for representing models that simulate human performance. A prospect for the 1980's is the analysis of learning considered as acquisition of knowledge, in which basic processes will involve modification and combination of cognitive structure. This development is likely to include, and profit from, analyses of learning tasks used in school instruction. (Author)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

CG

ED186801

PSYCHOLOGY OF LEARNING, 1960-1980: ONE PARTICIPANT'S OBSERVATIONS

James G. Greeno

25 February 1980

Technical Report No. 5

This research was sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-78-C-0022, Contract Authority Identification Number, NR 157-408.

This report is issued by the Learning Research and Development Center, supported in part as a research and development center by funds from the National Institute of Education (NIE), United States Department of Health, Education, and Welfare.

Reproduction in whole or part is permitted for any purpose of the United States Government.

Approved for public release; distribution unlimited.

CG 014368

U S DEPARTMENT OF HEALTH, EDUCATION & WELFARE
NATIONAL INSTITUTE OF EDUCATION

THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT. POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL NATIONAL INSTITUTE OF EDUCATION POSITION OR POLICY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: Technical Report No. 5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): PSYCHOLOGY OF LEARNING, 1960-1980: ONE PARTICIPANT'S OBSERVATIONS		5. TYPE OF REPORT & PERIOD COVERED: Technical Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): James G. Greeno		8. CONTRACT OR GRANT NUMBER(s): N00014-78-C-0022
9. PERFORMING ORGANIZATION NAME AND ADDRESS: University of Pittsburgh Learning Research & Development Center Pittsburgh, PA 15260		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Prog. Ele.: 61153N Proj.: RR 042-06 Task Area: RR042-06-02 Work Unit: NR 157-408
11. CONTROLLING OFFICE NAME AND ADDRESS: Personnel & Training Research Programs Office of Naval Research (Code 458) Arlington, VA 22217		12. REPORT DATE: 25 February 1980 13. NUMBER OF PAGES: 49
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report): Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This research was also supported by the Learning Research and Development Center, supported in part as a research and development center by funds from the National Institute of Education (NIE), United States Department of Health, Education, and Welfare. American Psychologist, in press.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

learning theory
stochastic models
memory processes
organizational knowledge

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

By 1960 there was a strongly developed theory of learning in which learning was considered as change of behavior. Neobehaviorist theories and then formal stochastic models analyzed processes in which probabilities of responses are altered. In the 1960's we began to analyze learning as discrete change between states of knowledge or stages of processing that differ in qualitative characteristics; stochastic models were used to represent these states and stages. In addition, the processes and structure of human memory were studied in detail.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

In the 1970's we have developed detailed analyses of the organization of knowledge for understanding language and solving problems, using programming languages as formalisms for representing models that simulate human performance. A prospect for the 1980's is the analysis of learning considered as acquisition of knowledge, in which basic processes will involve modification and combination of cognitive structures; this development is likely to include and profit from analyses of learning tasks used in school instruction.

PSYCHOLOGY OF LEARNING, 1960-1980: ONE PARTICIPANT'S OBSERVATIONS

James G. Greeno
University of Pittsburgh

Abstract

By 1960 there was a strongly developed theory of learning in which learning was considered as change of behavior. Neobehaviorist theories and then formal stochastic models analyzed processes in which probabilities of responses are altered. In the 1960's we began to analyze learning as discrete change between states of knowledge or stages of processing that differ in qualitative characteristics; stochastic models were used to represent these states and stages. In addition, the processes and structure of human memory were studied in detail. In the 1970's we have developed detailed analyses of the organization of knowledge for understanding language and solving problems, using programming languages as formalisms for representing models that simulate human performance. A prospect for the 1980's is the analysis of learning considered as acquisition of knowledge, in which basic processes will involve modification and combination of cognitive structures; this development is likely to include and profit from analyses of learning tasks used in school instruction.

MAR 2 1 1980

PSYCHOLOGY OF LEARNING, 1960-1980: ONE PARTICIPANT'S OBSERVATIONS

James G. Greeno
University of Pittsburgh

This paper presents my personal view of some recent history. It reflects my feelings of both nostalgia and optimism. I am nostalgic both about the state of the psychology of learning in the late 1950's and about the progress that I believe has been made in the field during the 20 years that have intervened. I am also optimistic that we now have the capability of developing a fundamentally new conception of the nature of learning, and that this, together with the accomplishments that are already in place, will constitute a contribution to human thought and culture of the strongest kind.

I will trace one sequence of recent developments in the psychology of learning and cognitive processes. This is not a complete, or even a balanced, view of the important events in the psychology of learning during the past two decades. The achievements that I consider here have formed one significant strand in the web of psychology's development during this period. This strand has two main threads: one mainly methodological, the other substantive. The methodological thread involves formal methods that have been adopted and developed by psychologists. These methods have permitted more precise statements of psychological hypotheses and more rigorous derivations of their implications. The substantive thread has been the development of more differentiated concepts and detailed characterizations of psychological processes and structures.

I will begin with a brief sketch of the developments that I will consider. In the 1950's, we had a fairly complete formal analysis of learning considered as change in the probabilities of responses. The main concepts of this analysis were worked out by neobehaviorists, with Hull's theory being the most rigorous version. In analyses developed during the 1950's formulas describing change in response probability are derived from stochastic models of the learning process.

In the 1960's, structural models of learning and memory were formulated using the theory of finite stochastic processes. This formalism provides a natural representation of transitions between discrete states of knowledge or stages of processing differing in qualitative characteristics.

A development that has occurred primarily in the 1970's is the analysis of the detailed structure of knowledge using formalisms consisting of computer programming languages. These models provide specific hypotheses about the cognitive processes and structures involved in solving problems and understanding language.

An important prospect for the 1980's is the development of a theory of learning involving detailed analysis of the acquisition of knowledge structures such as those that are required for understanding language and solving problems. This will provide understanding of learning as a process of modifying and combining cognitive structures, and will be applicable to the analysis of processes by which children acquire knowledge and skill in school instruction. In fact, I believe that theoretical analyses of learning tasks given to children in schools will be particularly useful for development of general theoretical concepts about the acquisition of knowledge.

The remainder of this paper presents brief personal comments on each of the three main developments that I have mentioned: neobehaviorist theory and analysis of response probability, discrete models of qualitative changes in knowledge and stages of processing, and programmed simulations of the detailed structure of knowledge and cognitive processes. Finally, I will comment on the prospect, as I see it, for developing significant new understanding of learning during the next few years.

Learning as Change in Behavior

Neobehaviorist theories. I became a participant in the psychology of learning in the late 1950's, when the issues that dominated investigations of learning were those generated by the theories of Guthrie (1935), Hull (1943), Skinner (1938), Spence (1956), and Tolman (1932). The questions that we hoped to answer, or at least to understand better, included the following: Can learning occur simply because of contiguity between stimuli and responses, or is reinforcement required? Do animals learn the location where food has been found, or do they simply learn to respond in ways that have been followed by food reinforcement? Does experience in an environment produce latent learning--that is, knowledge that is not seen in performance until incentives are changed to influence performance? If withholding reinforcement is the cause of response extinction, then how can we understand greater resistance to extinction following training with partial reinforcement? There were many other similar questions, of course.

It seems fashionable among cognitive psychologists now to regret the extent to which the psychological study of learning was dominated

by behavioristic ideas from the 1930's through the 1950's. In my admittedly nostalgic judgment, this regret overlooks achievements of great importance. Two important properties of scientific knowledge about a phenomenon are an explication of the processes that produce the phenomenon and an ability to relate hypotheses about the underlying hypotheses to data in an unambiguous way. As a result of neobehaviorist theorizing, these properties become established as attainable features of the analysis of active mental processes.

The neobehaviorists were not the first to develop psychological analyses with these characteristics. In particular, sensory processes were understood in terms of their neuroanatomical components, and psychophysics was an impressively formal enterprise. However, the psychological processes studied in sensation and psychophysics were understood as substantially receptive and passive in nature. Neobehaviorists took up the analysis of active mental processes, including choice, thought, and learning, and succeeded in developing plausible analyses of component subprocesses as well as the beginning of a formal representation of psychological hypotheses about these responsive psychological processes.

The analysis of component mechanisms in learning had been in progress, of course. A notable landmark, to use Kimble's (Note 3) felicitous term, had been the contributions of Ebbinghaus, Pavlov, and Thorndike, in which phenomena of learning were conceptualized as acquisition of associations, conditioned reflexes, and stimulus-response bonds. Neobehaviorists developed these ideas in great detail, especially Pavlov's and Thorndike's, and related their theoretical concepts and principles to a large and coherent body of experimental data.

One aspect of the theoretical development of the 1930's and 1940's was of special substantive importance. This was the detailed theoretical and empirical analysis of relationships between motivation and experience, the so-called learning-performance distinction. In its emphasis on issues such as the incentive value of reinforcing stimuli and the interaction of drive states induced by different kinds of deprivation, the neobehaviorist theory was as much a theory of motivation and choice as it was a theory of learning. Hull gave special emphasis to physiological deprivations as sources of motivation. Hull's idea, that learning provided a tendency to repeat actions that had led to reduction of physiological drives, made learning a critical process in the survival of individuals and species; indeed, it is as legitimate to classify Hull as a functionalist as it is to classify him as a behaviorist, as Kimble (Note 3) has pointed out. This feature of neobehaviorist theory, clearest in Hull, provided a strong conceptual link between the psychology of learning and biological science. Today, we recognize that the picture of organisms driven toward homeostasis, choosing responses that were previously followed by drive-reducing reinforcement, is a gross oversimplication. However, it was plausible when it was advanced, and the connection it provided with concepts in the established science of biology contributed significantly to establishing the psychology of learning as a legitimate scientific enterprise.

In addition to developing more detailed analyses of component processes of learning, neobehaviorists related their theoretical concepts and principles to empirical data in a systematic and detailed way. Here, too, Hull provided the strongest version of the neobehaviorist program. Hull constructed an imposing formalism in which explanations of phenomena

were presented as chains of deductions involving functional relationships among hypothetical variables. In retrospect, we realize that Hullian theory received more points for its formalism than were really merited by the rigor of the system (cf., Koch, 1954). Nonetheless, the achievements of the Hullian formalism were a notable advance and established formal theoretical analysis as a feasible goal in the psychology of learning.

Stochastic process models. The formal analysis of learning was continued during the 1950's, notably by Bush and Mosteller (1955), Estes (1950, 1959), and Luce (1959). Like Hull's, these analyses considered learning as change in the probabilities of responses; however, they provided a deeper analysis. The models of learning developed in the 1950's included assumptions about the quantitative effects of specific events that occur on trials in a learning experiment. The form of the learning curve can be derived from these assumptions, and thus becomes useful as evidence in testing alternative hypotheses. It is historically interesting that Thurstone (1919, 1930) had proposed such models somewhat earlier, but his theoretical proposals did not lead to substantial experimental programs or theoretical extensions. The critical difference might be that in the 1920's, quantitative methods in psychology were primarily applied to measurement and scaling, while by the 1950's, primarily because of Hull's work, it was evident that formal theoretical methods could be used in answering substantive questions about processes of learning. For whatever reason, the formal theoretical analysis of learning was an important achievement of the 1940's and 1950's in which Hull was the major early figure, and by about 1960 a set of theoretical

methods and concepts had been developed that provided a basis for an analysis of psychological processes in learning at a more detailed level.

Verbal Learning and Stochastic Models

The development of general behavior theory was the major activity in the psychology of learning in the 1940's and 1950's, but other things were going on as well. One significant alternative to general behavior theory was the study of rote verbal learning. The tradition of experimental study of rote learning went back to Ebbinghaus, but most of the literature on the topic has been produced by American functionalists such as McGeogh, Postman, and Underwood. The major concepts developed in this study were concerned with processes of strengthening and weakening of associations, and these were incorporated into a body of concepts referred to as interference theory. These concepts were strongly influenced by general behavior theory. Information about the correct responses in paired-associate memorizing was interpreted as reinforcement, forgetting in some circumstances was interpreted as extinction, and transfer of training was interpreted as stimulus and response generalization (cf., Underwood, 1964). On the other hand, the principles of verbal learning, transfer and forgetting remained relatively informal, in contrast to the formalization developed in the Hullian theory of response conditioning and stochastic models of changes in choice probabilities. Some investigators believed that the processes of verbal learning were more complex than those of instrumental and classical conditioning, and therefore more empirical knowledge was needed to provide a sound basis for formal theory. This view was reinforced

by an earlier attempt--by Hull, as it happened (Hull, Hovland, Ross, Hall, Perkins, & Fitch, 1940)--to provide a formal theoretical analysis of serial verbal learning, and another attempt by Gibson (1940) to formalize part of the theory of verbal learning involving discrimination among items. Hull's analysis turned out to be extremely cumbersome, and Gibson's theory omitted important aspects of the memory process (Underwood, 1961).

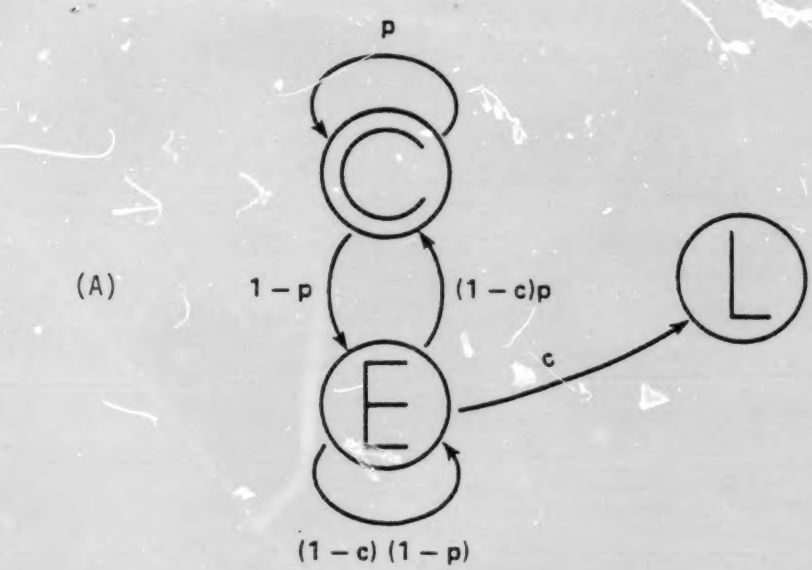
Finite stochastic models of learning. In the 1960's a formalism was applied to analyze phenomena of verbal learning. The formalism was the theory of finite stochastic processes. The analyses were a natural extension of the stochastic models developed in the 1950's and applied primarily to animal conditioning and to performance by human subjects in a task initially called verbal conditioning and later referred to as probability learning (e.g., Estes & Straughan, 1954). However, beginning with Bower's (1961) analysis of paired-associate memorizing and Restle's (1962) analysis of simple concept identification, a substantial body of literature developed involving analyses of the learning of paired associates (e.g., Polson, Restle, & Polson, 1965), memorizing lists of items for recognition and free recall (e.g., Kintsch & Morris, 1965), and induction of simple rules for classifying stimuli (e.g., Bower & Trabasso, 1964).

The important innovative idea in this development was to conceptualize learning as discrete change between states of knowledge rather than as change in probability of response. A major factor in the development was that successful analyses were achieved using extremely simple models.

One finding was that performance of adult human subjects in simple concept identification is described well by the model pictured in the Panel A of Figure 1. The task requires a subject to discover a simple rule for classifying stimuli. On each trial, a stimulus is presented, the subject gives a category response, and then is told which category that stimulus belongs to. The model in Panel A was originally proposed by Restle (1962), who showed that it follows from assuming that subjects select samples of hypotheses, choose category responses based on the hypotheses they have on each trial, remove incorrect hypotheses after each correct response, and resample with replacement after each error.

Insert Figure 1 about here

The idea of solving concept-identification problems by a process of active selection and test of hypotheses was not new, of course (Bruner, Goodnow, & Austin, 1956; Woodworth, 1938). However, the simplicity of the process as represented by the Markov model was quite surprising. According to the model in Figure 1, the probability of solving the problem is a constant, c, that applies each time an error occurs, regardless of how many errors have occurred previously. This all-or-none property is particularly incompatible with the idea that correct responses are gradually strengthened in association with relevant aspects of stimuli. Therefore, Bower and Trabasso's (1964) experimental results which gave strong and surprising support that concept identification performance is described well by the model in Panel A of Figure 1, produced an interesting twist in comparison between human and animal performance



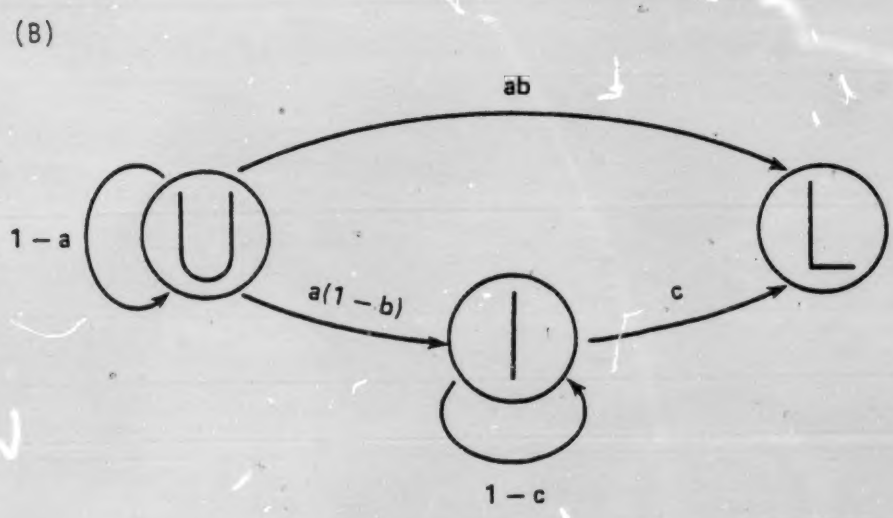


Figure 1. Finite stochastic models: (A) of concept identification, and (B) of paired-associate memorizing.

in this task. The task called concept identification when human subjects participate is called discrimination learning when the experiment is run with laboratory animals. It was established that active selective attention is an important feature of animal learning in the discrimination task, just as it is for humans (e.g., Lawrence, 1963). However, the process of learning is apparently more complicated when a rat learns a discrimination than when a person identifies a concept for use in classifying stimuli. In learning by rats the selective process apparently is modified in a gradual fashion, and the subjects do not respond as systematically to the stimulus attributes that they attend do (Lovejoy, 1968). Thus, in contrast to the earlier belief by some behaviorists that studies of animal conditioning would reveal simple forms of principles that would appear in more complex form in human learning, the opposite seems to have occurred in this case.

Another result involving a surprisingly simple model was Bower's (1961) application of a two-state Markov model to paired-associate memorizing. Combined with Rock's (1957) and Estes' (1960) more qualitative evidence, Bower's results provided support for the startling idea that in the simplest case, learning of an association is an all-or-none event, and thus should be viewed as a discrete transition between an unlearned and a learned state. Evidence for incremental learning was provided (e.g., Postman, 1963); however, in retrospect, it seems reasonable to consider the all-or-none model as an ideal case, perhaps analogous to the idea in physics of a frictionless gas. The fact that all real experiments depart from the ideal model, to varying degrees, does not invalidate the model as a useful and fundamentally correct characterization (cf., Crowder, 1976).

Further work on paired-associate memorizing led to a hypothesis about the nature of the basic one-step process of paired-associate memorizing, and the nature of the additional process that is required when memorizing is significantly discrepant from the all-or-none model. In this work, the slightly more complicated model graphed in Panel B of Figure 1 turned out to be useful, especially in allowing estimates of parameters that enabled judgments about the relative difficulty of stages of learning in different experimental conditions. A considerable body of evidence, much of which depends on use of the model in Panel B, appears to support the idea that the two main stages of paired-associate memorizing involve storage of relational units representing the pairs and formation of a retrieval system, perhaps in the form of a network, that enables the subject to retrieve individual items on tests (Greeno, James, DaPolito, & Polson, 1978). For an alternative interpretation of some of these findings, see Postman and Underwood (1973).

Structure and processes of memory. Another elaboration of the basic all-or-none model involved postulating a transient state corresponding to an item's being held in short-term memory (Atkinson & Crothers, 1964; Greeno, 1967). However, the major development of theories analyzing components of the human information processing system have treated the process in more detail. As a result of this work (e.g., Atkinson & Shiffrin, 1968; Norman & Rumelhart, 1970) we are now aware of at least three memory systems: short-term sensory storage, short-term memory, and something less transient. I personally prefer the view graphed in Figure 2 that there is an intermediate-term memory system often called long-term memory in experimental applications and an organized system of memory for concepts and factual information. The general picture

that has become familiar is that information is received by a sensory system that has a very large capacity, but a holding time on the order of a fraction of a second. Information selected from that system is held in short-term memory, which has a much smaller capacity, but ordinarily holds items for a few seconds. If relationships can be found to organize this information it is stored in intermediate-term memory, in which case it will be held for a longer time--minutes or hours. The information may become integrated as a part of the individual's permanent structure of concepts and factual knowledge and thus become a part of the person's store of semantic and factual knowledge.

Insert Figure 2 about here

Along with these ideas about memory structure, considerable additional understanding of processes of memorizing has also been developed. Coding of information for memory was studied by numerous investigators (Melton & Martin, 1972). Recall of items from lists was analyzed in relation to rehearsal processes (Bernbach, 1969; Rundus & Atkinson, 1970), and the way in which rehearsal was carried out (Woodward, Bjork, & Jongeward, 1973). Processing that involves retrieval of word meanings was found to provide a better representation for memory than processing involving more superficial features of the items (Craik & Tulving, 1972).

My purpose in rehearsing this set of familiar ideas is to contrast it with the conceptualization we had as recently as 20 years ago. To some extent, the discussions we now have about storing information involve translation of earlier discussion into new terms. Storage of information and learning of responses to stimuli are equivalent concepts

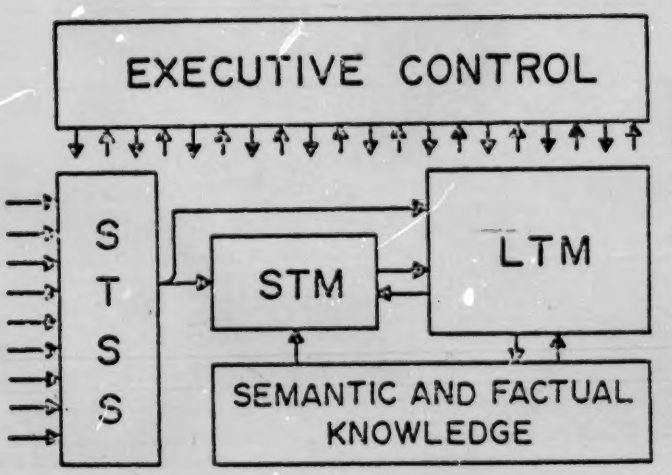


Figure 2. Divisions of information-processing function in the human memory system (from Greeno & Bjork, 1973).

at some level of abstraction. However, there have been genuine substantive changes in the theoretical issues investigated from the 1950's to current research. In the 1950's our discussion was in the terms of very general variables, most of them external to the learner. More recent discussion has involved more detailed analyses of the process of storing information in memory. For example, issues such as the following were important in the 1950's: Is it important to present reinforcement or knowledge of results immediately, or does delayed feedback provide an effective condition for learning? If new C-B associations are learned with the same responses as earlier A-B associations, will there be interference between those associations, presumably because of interference in the backward direction (B-A vs. B-C)? By 1970, we were also asking somewhat more detailed questions, such as: Is information maintained in short-term memory if a distracting task involves activity in a different modality? and Does storage in long-term memory require processing information meaningfully, rather than simple rehearsal that maintains the information in short-term memory? The more detailed analyses now available involving both processes and structural components of memory shows an important dimension of the progress made during the 1960's in our understanding of human cognition.

In addition to substantive matters such as these, the development of stochastic models of learning and memory included a significant methodological advance. The gist of the development was a technology for using data in more precise and detailed ways to test psychological hypotheses. Statistical methods traditionally used by experimental psychologists are designed to test the hypothesis that two groups are the same, or that the difference between two groups is the same as the

difference between two other groups. A majority of experiments have been designed to demonstrate the presence of an effect, so the result that supports a psychological hypothesis is one that falsifies the null hypothesis. However, with more detailed knowledge and theory about psychological processes, we can now formulate more specific hypotheses that imply definite patterns of experimental effects that should occur if the hypotheses are correct. Therefore, we need statistical methods that are designed to test whether the specific pattern of findings can be rejected, rather than general methods that merely test for the presence of experimental effects. Statistical methods for evaluating goodness of fit of models based on specific psychological hypotheses are now becoming quite commonplace. Such methods were applied and developed substantially in relation to stochastic models of learning (cf., Restle & Greeno, 1970).

Organization of Knowledge

Through most of the 1960's, most of us thought that we understood the basic principles by which knowledge is organized. We believed that knowledge of facts and concepts was a network of associations between ideas, and that knowledge of how to do things was a set of connections between stimuli and responses.

Conceptual and factual knowledge. Our conceptualization of the organization of knowledge has developed considerably since about 1970. The nature of knowledge of facts and concepts is represented in a variety of theories that are all based on the concept of a schema. We have known since Bartlett's (1932) famous work on memory for stories that schemata are critically important in cognitive functioning, but only recently we

have been able to specify the constituents of schemata in relatively definite ways (e.g., Norman & Rumelhart, 1975; Schank & Abelson, 1977).

Several current theories share the view that schemata are data structures or procedures that are used to organize the components of specific experience and to expand the representation of an experience or message to include components that were not specifically contained in the experience, but that are needed to make the representation coherent and complete in some important sense. For example, our knowledge of the meaning of a verb that denotes an action includes the ability to form a relational structure that connects the agent of the action, its object, the instrument used, and so on. The structure that is formed may also contain additional information that is inferred. An example of a schema representing the meaning of a verb is in Figure 3, taken from Gentner's (1975) analysis of possession verbs. This schema functions in an understanding system to process sentences such as, "Ida borrowed a tablecloth." The upper part of Figure 3 shows the results of a basic case analysis in which Ida is assigned as the agent of the action of borrowing, and the tablecloth is assigned as the object. The lower part of the diagram shows the results of expanding the schema into its definitional components involving knowledge that the action was performed by Ida, this caused a change in the possession of the tablecloth so that it came into Ida's possession from someone else's, and that Ida has an obligation to return the tablecloth to the person who had it before.

Insert Figure 3 about here

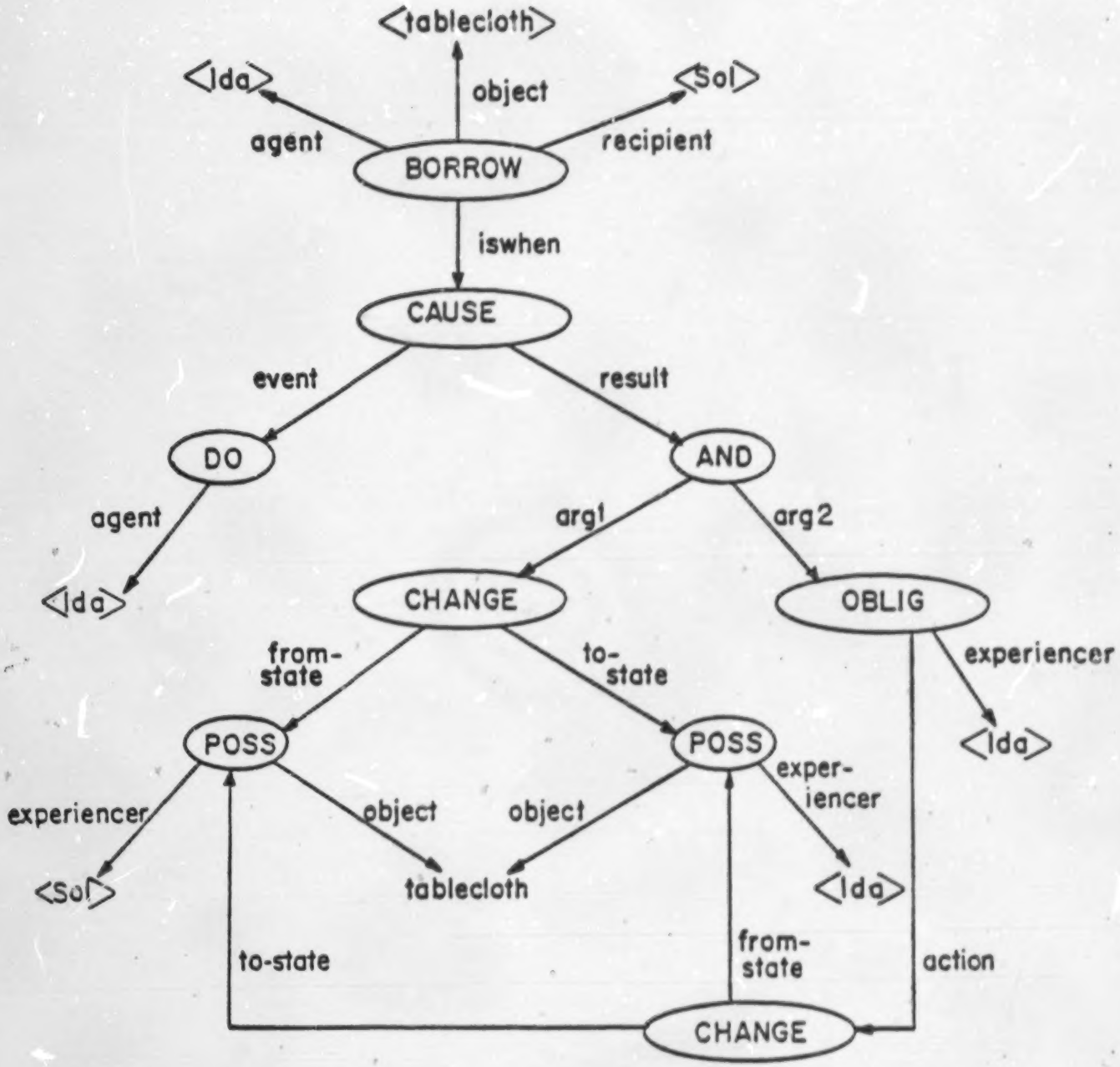


Figure 3. Schematic representing of the meaning of "borrow," and semantic information understood from the sentence "Ida borrowed the tablecloth" (from Gentner, 1975).

Theories based on the idea of schemata have also been developed to analyze the understanding of simple stories. In these analyses it is postulated that we use knowledge about principles of motivation and other psychological processes to fill in unstated connections so the story makes sense. An example from the work of Mandler and Johnson (1977) is in Table 1 and Figure 4. Table 1 presents the propositions of a familiar story. Figure 4 shows an integrated structure of relations among the propositions that is achieved in the process of understanding the story. The structure shown here includes formal relations involved in the story structure, such as the distinction between the setting of the story and the description of events in the story and the distinctions between the various parts of an episode--its beginning, development, and conclusion. The structure also includes relationships based on knowledge about individuals and things. It is understood that the connection between the state of wanting the meat that is seen in the water and the act of snapping at it is motivational, but the relation between snapping at the reflection and having the meat fall into the water is causal.

Insert Table 1 and Figure 4 about here

Knowledge for solving problems. In addition to analyses of language understanding such as these, we also have developed a considerably expanded conceptualization of the knowledge involved in doing things. Much of this theory has been developed in the analysis of problem solving, and Newell and Simon's (1972) work provided most of the seminal ideas in the recent theoretical developments. A salient feature of recent analyses

Table 1

Dog Story (from Mandler & Johnson, 1977)

1	It happened that a dog had got a piece of meat
2	and was carrying it home in his mouth.
3	Now on his way home he had to cross a plank lying across a stream.
4	As he crossed he looked down
5	and saw his own shadow reflected in the water beneath.
6	Thinking it was another dog with another piece of meat,
7	he made up his mind to have that also.
8	So he made a snap at the shadow,
9	but as he opened his mouth the piece of meat fell out,
10	dropped into the water,
11	and was never seen again.

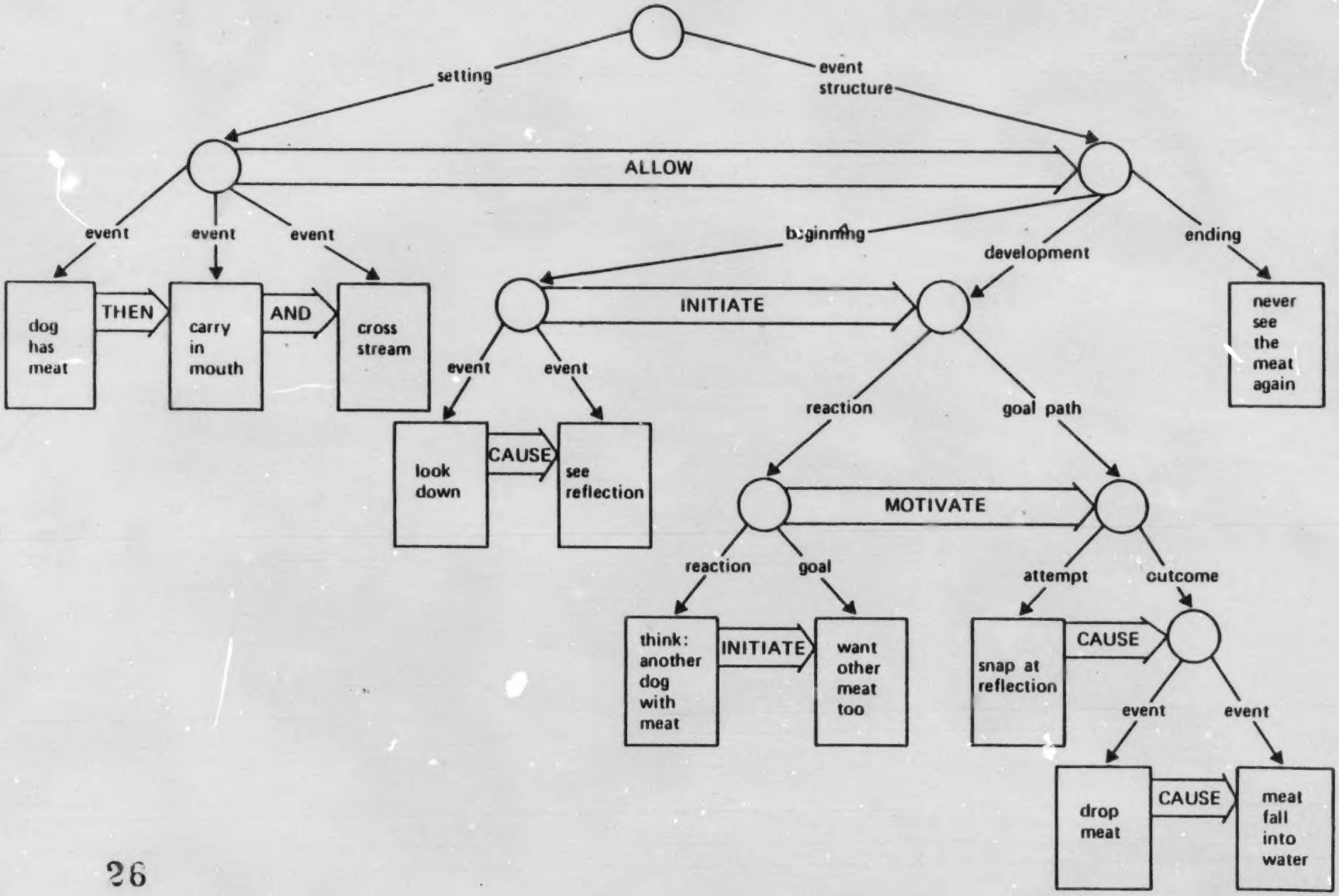


Figure 4. Structural network of information understood from the dog story in Table 1.

of problem solving has been the inclusion of processes that set subgoals and adopt plans, thus representing problem-solving strategies and explaining the organization of problem solvers' performance.

Knowledge for problem solving is frequently represented in the form of a production system. An example is in Table 2, which shows one of the strategies that Simon (1975) analyzed for solving the Tower of Hanoi puzzle. There are three pegs and some number of doughnut-shaped disks, graded in size. Initially the disks are on one of the pegs with the disks ordered in size starting with the largest on the bottom. The task is to move all the disks to another designated peg moving only one disk at a time and never covering a smaller disk with a larger one. Each component of Simon's model for solving the problem is a production, consisting of a condition paired with an action. On each cycle of the process, conditions are tested in order starting with P1. When one of the condition tests is passed the action of that production is executed and the system exits. For example, the initial values of State and Goal are null. Therefore, on the first cycle none of the conditions of P1-P5 are satisfied, so the default condition of P6 passes and the goal is set to move the pyramid of disks found on the initial peg onto the designated goal peg. On the second cycle State is still null so the first condition that passess is in P5. This produces a test to see whether the goal can be achieved by a simple move; the possible outcomes of this test are the following: Can if the goal involves a disk that can be moved and no smaller disk on the desired peg; Can't if pyramid to be moved has more than one disk or a smaller disk is on the desired peg; Done if the pryamid is already on the desired peg; and Problem-solved if all the disks are on the designated goal peg. The result of the test becomes the value

of the State variable. Usually, the first test results in State having the value Can't, so on the third cycle the production that fires is P4. This has the action of setting a goal of moving a smaller pyramid. When a small enough goal is set, the test results in Can and a move is made (production P3). On the following cycle the test shows that the goal is Done, and then the system returns to a goal involving a larger disk (production P2).

Insert Table 2 about here

A slightly more complex formalism for representing knowledge for performing actions is called a procedural network (Sacerdoti, 1977). In a procedural network each action is associated with preconditions that must be present for the action to be performed. Each action is also associated with its consequences and with other actions that constitute components of the action. In a production system each action is associated only with its preconditions, and the coordination of actions must occur because of the way in which the productions are written and the sequence in which tests occur. The additional structure of a procedural network can be used by a planning mechanism that considers consequences of actions in relation to preconditions of actions that will have to be performed later. A procedural network also provides a basis for analyzing the relations among actions that occur at different levels. Figure 5 shows a diagrammatic representation of a procedure for subtracting numbers, developed by Brown and Burton (1978). Each action is associated with component actions that are performed as part of the more global action. For example, the action called Subtract Column includes a procedure for determining whether borrowing is needed, a procedure for

Table 2

Production System for Tower of Hanoi (from Simon, 1975)

P1. State = Problem-solved ⟶ Halt

P2. State = Done, Goal = Move(Pyramid(k),A)
⟶ Delete(STM), Goal ← Move(Pyramid(k−1),A)

P3. State = Can, Goal = Move(Pyramid(k),A)
⟶ Delete(STM), Move(k,P(k),A)

P4. State = Can't, Goal = Move(Pyramid(k),A)
⟶ Delete(STM), Goal ← Move(Pyramid(k−1),O(P(k),A))

P5. Goal = Move(Pyramid(k),A) ⟶ Test(Move(k,P(k),A))

P6. else ⟶ Goal ← Move(Pyramid(n),Goal-peg)

borrowing, and a procedure in which the answer for the column is found. Figure 5 is highly schematic; many tests for appropriateness of subactions are required, but are not shown in the diagram. However, Figure 5 is sufficient to illustrate the general idea of a procedural representation, as well as the fact that apparently simple performances such as subtraction turn out to be surprisingly complex when they are analyzed in detail.

Insert Figure 5 about here

In my own recent research, I have been investigating tasks that seem to involve both conceptual and procedural knowledge. One line of research has involved investigating problem solving in geometry, where each step in solving a problem involves an inference similar in kind to those that are standard in the theory of language understanding. A model of geometry problem solving that has been developed uses a representation of the problem situation in the form of a semantic network. The procedures for solving problems are in the form of a production system, modeled after Anderson's (1976) ACT system. The process of problem solving is a process of making semantic inferences. However, they are goal-directed inferences, related to the problem-solving task, so the system combines important features of problem solving with inferential processes involved in understanding. As an example, Panel A of Figure 6 shows a simple geometry problem. Panel B shows some components of the initial representation of the problem in the system; the measure of one angle is given, and the goal is to find the measure of another angle. Panel C shows a structure formed in the process of solving the problem. Note

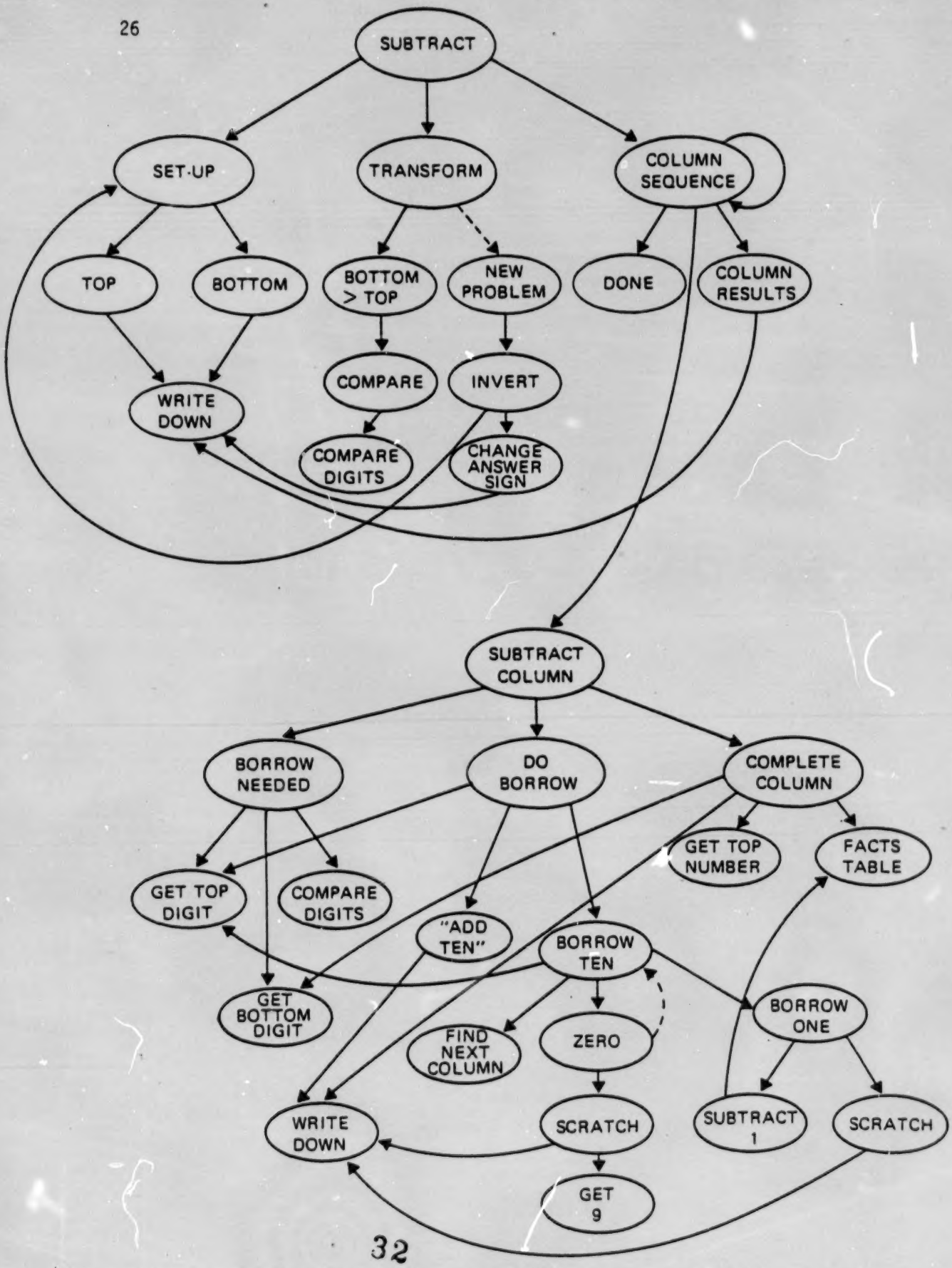


Figure 5. A procedural network for subtraction (from Brown & Burton, 1978).

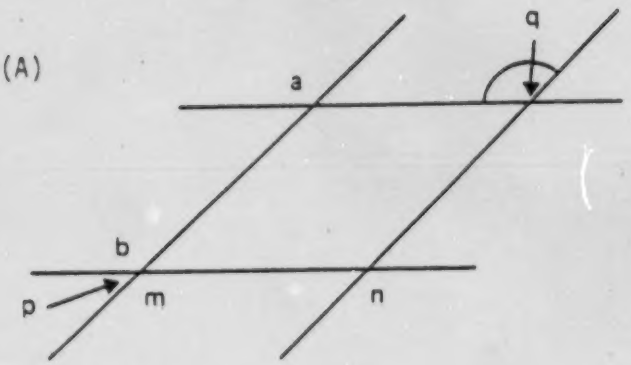
that the initial goal has been satisfied: A12 is linked to a measure of 140^{o}. The structure also includes other properties and relations that were generated in the process of reaching the solution, for example, that A1 and A6 are vertical angles and are therefore congruent. (Research on geometry has been reported in Greeno, 1976, 1977, 1978.)

Insert Figure 6 about here

Another line of research involves study of the process of solving arithmetic word problems. In this work I am collaborating with Joan E. Heller and Mary S. Riley. The word problems we are studying are essentially question-answering tasks. Some quantitative information is given, and an inference is required to find the answer. An example of the kind of problem we are studying is the following: "Joe has five apples; Tom has three more apples than Joe. How many apples does Tom have?" The inferential process required for these problems is specified in arithmetic--the answer is found by adding 5 + 3 . However, the process of solving the problem includes an important component of language understanding in which the problem solver comprehends the given information and the question. The process of understanding is required in order to select the appropriate arithmetic procedure for calculating or inferring the answer.

The research that we are conducting includes the development of a model of the process of understanding word problems and selecting the arithmetic operations to be performed. The understanding process is like those generally included in theories of language processing. Sentences found in text are translated into a cognitive representation that

(A)



Given a ∥ b, and m ∥ n,
measure of ∠p = 40°.
Find the measure of ∠q.

(B)

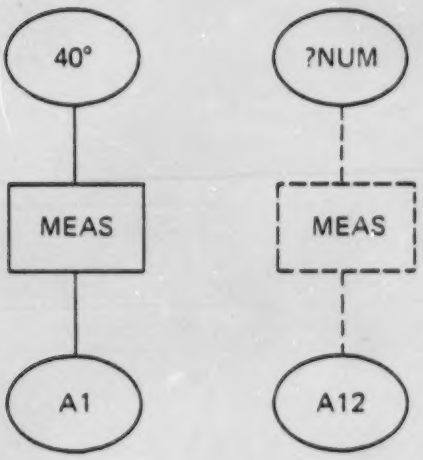


Figure 6

(A) a problem in geometry;

(B) initial representation of the problem (MEAS = measure; A1 and A12 refer to angles);

(C) cognitive representation after solution, including other angles used in the solution (CONG = congruent, SUPP = supplementary, VERT = vertical angles, CORR = corresponding angles, INTSAM = interior angles on the same side of a transversal; A1, A6, A8, and A12 refer to angles.)

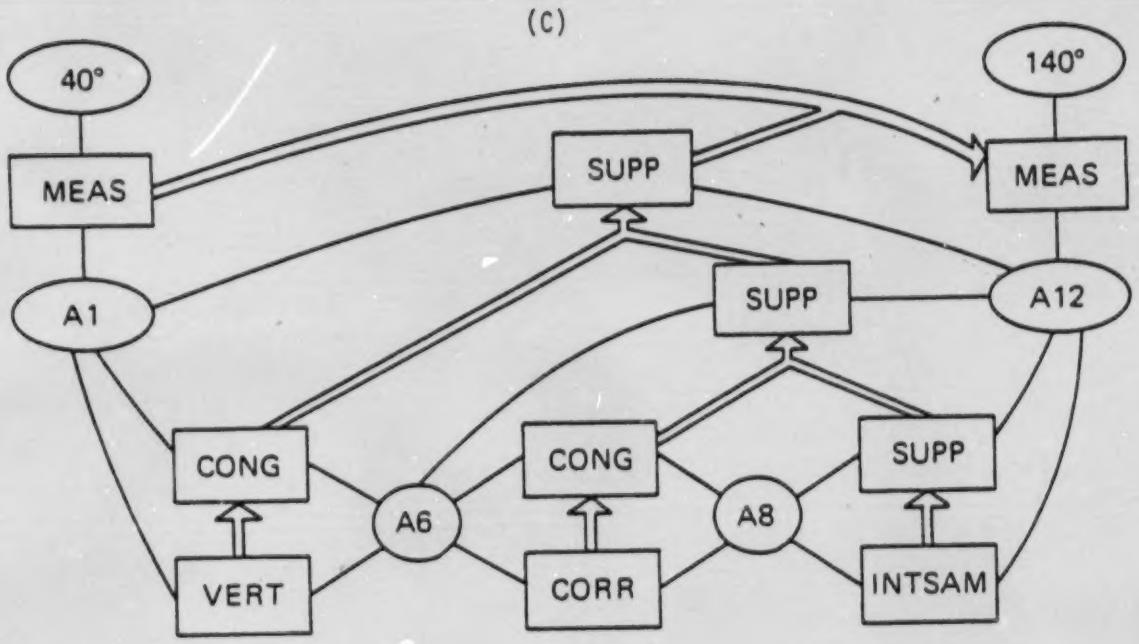


Figure 6 (continued)

(A) a problem in geometry;

(B) initial representation of the problem (MEAS = measure; A1 and A12 refer to angles);

(C) cognitive representation after solution, including other angles used in the solution (CONG = congruent, SUPP = supplementary, VERT = vertical angles, CORR = corresponding angles, INTSAM = interior angles on the same side of a transversal; A1, A6, A8, and A12 refer to angles.)

indicates the main relationships among the concepts mentioned in the text. Our use of schemata is similar to other language-understanding systems that have been developed, although the schemata in the system are somewhat more abstract than those that have been studied in the analysis of sentence and story understanding.

An example is in Figure 7, showing a schema that is used in understanding the most common kind of problem involving simple addition or subtraction. This schema applies to a problem that describes a situation involving a quantity, some event that changes the quantity by some amount, and a quantity that results from the change. An example would be, "Tom had five apples; Joe gave him some apples and now Tom has eight apples. How many apples did Joe give him?" The understanding system determines that the object involved is a set of apples in Tom's possession, and the amount it has initially (the state labeled from) is five. The amount involved after the change (the state labeled to) is eight. The action has a direction of increase, and the amount involved in the action is unknown. With this configuration of information and the question, the system selects an operation of subtraction to find the answer.

Insert Figure 7 about here

The part of the model that has been developed has three general schemata for solving simple addition and subtraction problems. In addition to the schema in Figure 7 involving an event that changes a quantity, there are schemata for representing combinations of quantities and comparisons of quantities. These three semantic structures seem sufficient to provide understanding of all the simple one-step addition and

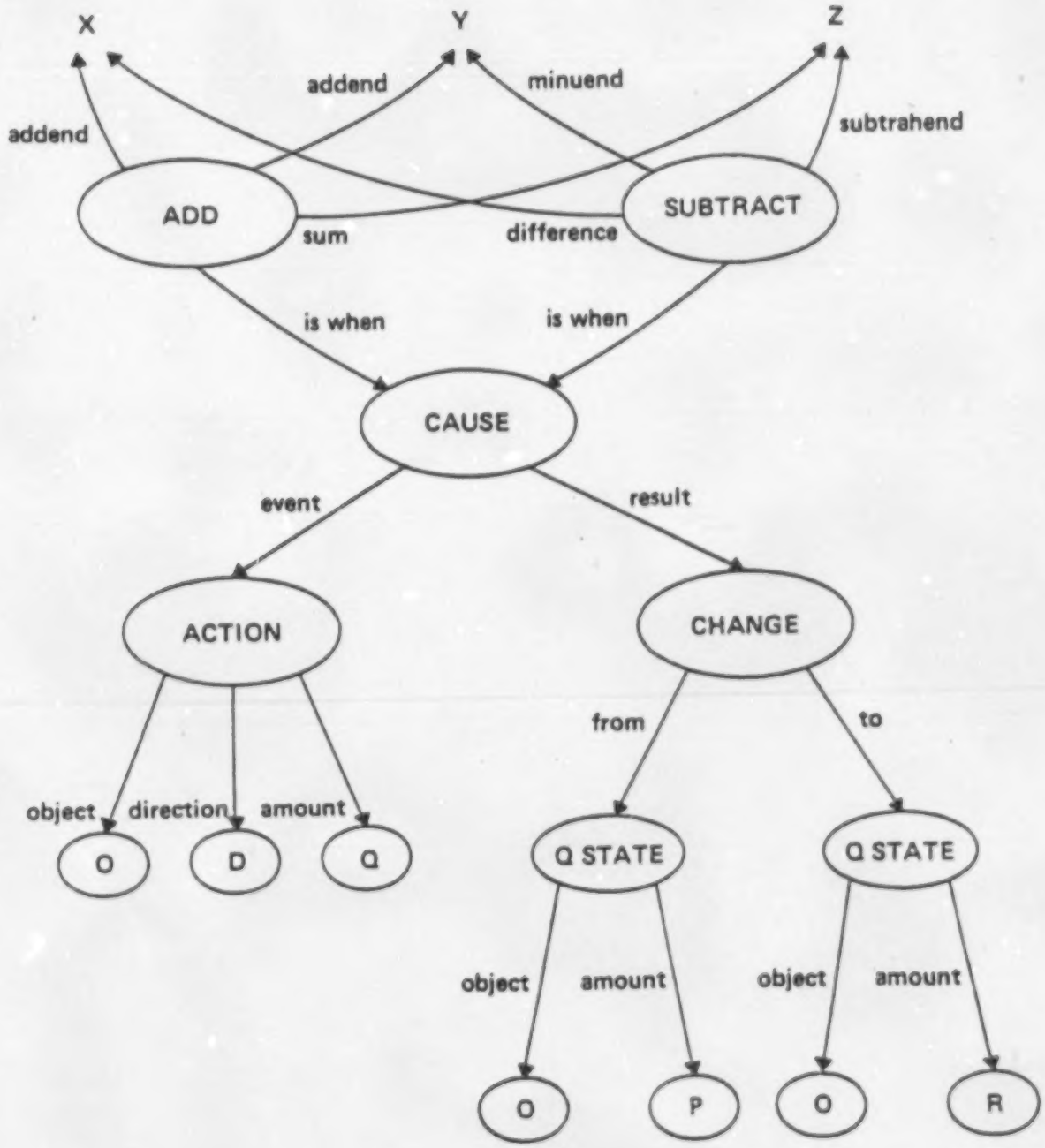


Figure 7. Schema for representing arithmetic problems in which an event causes a change in quantity.

subtraction problems that children are expected to be able to solve (Heller & Greeno, Note 2), and we have obtained evidence that the semantic structure of a problem is a relevant factor in determining the difficulty of the problem (Riley & Greeno, Note 5).

These studies of geometry and arithmetic problem solving relate to the general issue of the relation between understanding processes and knowledge of problem solving procedures. There are other investigators working on this general problem, of course. Hayes and Simon (1974) have studied the process of understanding text that presents instructions for solving problems. A number of investigators (de Kleer, Note 1; McDermott & Larkin, 1978; Novak, Note 4; Simon & Simon, 1978) have studied the process of solving physics problems, emphasizing the relation between knowledge of formulas and understanding of general concepts and relationships. Many of the important principles were included in Winograd's (1972) system that understood instructions for changing positions of toy blocks. These various projects all are promising for the prospect that current work will lead to a considerable strengthening of our understanding of relationships between processes involved in understanding language and procedural knowledge that is involved in skilled performance.

An aside about methodology. An important part of the development of recent theories that include representations of knowledge has been the use of formalisms that have not been used commonly in psychology. These include semantic networks, production systems, and procedural networks. There are many different impressions about these new formalisms, especially since their use generally requires writing computer programs. My impression about these formalisms, and the role of computer

programming in psychological theorizing, is somewhat different from what I take to be a commonly-held view.

We are all aware that by choosing a formalism, one places some constraints on the form of a theory that will be developed using that formalism. Many people seem to have the impression that when theories are formulated as computer programs, we are constrained to model psychological processes as though human minds were digital computers. I believe that this impression is seriously mistaken. In my opinion, the real constraints that are imposed on theorizing are at a much more specific level than the computer.

There are substantive constraints imposed by the choice of a formalism such as a semantic network or a production system. These constraints are analogous to those that were imposed on our theorizing some years ago when we chose to represent learning processes as Markov chains. There were alternative formalisms available then, as there are now. Learning could be considered as a change in one or more continuous variables, rather than as discrete transition in a finite state space. If learning was assumed to involve continuous variables, then the formalism of differential equations provided a helpful framework for representing hypotheses. Many of us found the formalism of discrete stochastic processes more helpful, however, and the models we formulated using that framework seemed in better agreement with experimental data than those that considered learning as continuously graded change. It does not seem to be possible to falsify a formalism with empirical evidence. For example, data that are explained naturally by a model written in the formalism of a Markov chain can also be explained by assuming changes in a continuous variable (Restle, 1965). However, there are considerable

differences in the degree to which different ideas can be expressed naturally and conveniently in a formalism, and because of that the choice of a formalism influences the development of theory. I have no doubt that our use of semantic networks of the kind that are used in schema theories of language understanding and our use of production systems in the theory of problem solving are influencing the substantive concepts that are included in our theoretical analyses of these processes.

At one higher level of generality, when we develop a model in one of these formalism, we use a programming language. The current favorite in the United States is LISP, because of its convenience for programming procedures that operate on symbols, but other languages have been used and still are used in some applications. I believe that the role of a programming language in the development of a theory is analogous to the role of a general mathematical system, such as algebra or calculus, in the kinds of mathematical models that are more familiar psychology. A programming language provides a notation for representing ideas, and it provides some rather general methods for performing derivations. The main reason for choosing a programming language is its convenience for representing the kinds of ideas that are important in a theory. For representing ideas about many psychological processes, LISP is much more convenient than many other languages such as FORTRAN. This has important practical consequences in the actual work of developing a theory, but I believe it has very little impact on the substance of a theory.

The computer itself is still another level removed from the substance of a theory. My impression is that the computer imposes no substantive constraints on theory at all. This is not to say that the

computer is unimportant. The computer enables a theorist to test whether the assumptions of the theory fit together in a mutually consistent way, and whether the assumptions really imply what the theorist believes that they imply. Theories of language understanding and of problem solving have too many component processes to permit a reliable judgment of consistency and sufficiency for observed performance unless the theory is written out in the form of a program and run on a computer. Then the computer provides a way of keeping track of the various components and their interactions.

It is not unusual for a scientific theory to be written out so that derivations can be performed in an explicit way. Usually, the device we use for making derivations is a piece of paper or a blackboard. A good blackboard can be a great help in working out the details of a theory, and so can a good computer. Sometimes the theoretical task at hand requires a rather large blackboard, and the one in your office is insufficient; this holds for computers as well. However, the way that a blackboard works has no consequences at all for the kinds of assumptions that we put into our theories, and I believe that the properties of computer hardware are also completely irrelevant to the substantive aspects of psychological theories that we formulate as computer programs.

Learning As Acquisition Of Knowledge

Psychologists who have emphasized investigation of the organization of knowledge during the 1970's have focussed attention on the question of what is learned, rather than how learning occurs. With fundamentally new ideas about the outcome of the learning process, we should expect some important new developments in the theory of learning. We now realize

that someone who has learned the concepts of a language has acquired a large collection of schematic knowledge structures that enable representation of relationships among a set of concepts when sentences using those concepts are understood. We also realize that someone who has learned to solve a class of problems has acquired a set of cognitive procedures including actions that change problem situations as well as procedures for setting goals and for planning. The theory of learning should include analyses of the processes by which knowledge structures of these various kinds are acquired. Learning must include processes for organizing and integrating information and procedures, as well as for storing them. We now realize that the learning system has capabilities for holding information at various stages of memory. The theory of learning should clarify the ways in which the various holding capabilities enable the processing of information and procedures that have been organized to varying degrees, permitting their further analysis and synthesis for representation in memory.

The study of learning in this new context is in an early stage; most of the ideas that are needed have yet to be worked out. However, the beginnings of some analyses have been developed, and may provide a preliminary indication of the shape that the new theory is likely to have.

It should be recognized that theories of language processing and problem solving already include elementary forms of learning. When a sentence is understood, new information is stored in memory, and the fact or other information expressed by the sentence is learned. When a problem is solved, new information is generated by the system and stored in memory about the specific characteristics of the problem situation and the specific goals and actions included in the solution

of that problem. The information stored in memory when a story is understood or when a problem is solved can be tested by asking questions; question answering based on story understanding has been analyzed by Lehnert (1978), and questions about problem solutions are answered by Winograd's (1972) problem-solving system. The role of short-term memory limitation has been worked out in a preliminary way by Kintsch and Vipond (1979) for comprehension of text, and by Atwood and Polson (1976) for solving simple problems.

The learning that occurs in understanding sentences or stories or in solving specific problems is a form of assimilation, where new specific information is acquired by fitting it to existing general cognitive structures. More significant theoretical problems arise when we consider the modification of general schemata for understanding or general procedural knowledge used in problem solving.

Development of new structured schemata as complex as the one shown in Figure 3 has not yet been analyzed. However, a theoretical analysis of acquisition of schemata for classifying simple stimuli has been given by Anderson, Kline, and Beasley (1979). Anderson et al's system learns in a categorization task by adding production rules with conditions that incorporate features of stimuli and actions that perform the category responses. The productions are formed on the basis of plausible principles of generalization and discrimination, productions are strengthened and weakened on the basis of principles that are reasonable on general grounds, and a knowledge structure results that is consistent with prototypical representations of concepts.

An analysis of learning from experience in problem solving has been given by Anzai and Simon (1979). This analysis showed how information

about the problem situation stored during solutions can lead to the development of new strategies in which performance is guided by more complex and sophisticated goals. Klahr and Wallace (1976) also have analyzed processes of acquisition of procedures in which operations used in quantitative judgments are acquired on the basis of invariant features that are detected in experience in quantitative tasks.

The conception of learning involved in these analyses is quite different from the one that guided our research on learning during the 1950's and 1960's. The learning tasks that we gave to subjects involved relatively unstructured materials because we felt that such tasks would inform us about basic learning processes, with minimal contamination of prior knowledge. If recent analyses are approximately correct, the knowledge structures acquired even in relatively simple task situations are very complex. It seems likely that to understand the acquisition of such structures, we need to know the ways in which complex cognitive structures are modified and combined. Basic principles of learning may be more easily discerned by observing interactions between new information and existing knowledge structure than they have been in situations where the effect of prior knowledge on learning has been minimized.

A pleasant prospect in the new study of learning that is emerging now is the revival of strong connections between the psychology of learning and the practice of instruction in schools. Until about 1930, the linkage between experimental psychology and instructional psychology was reasonably strong; examples of experimental applications and analyses in early mathematics instruction include Thorndike (1922), Judd (1927), and Brownell (1928). However, with a few notable exceptions such as Bruner (1966), Piaget (1970), Skinner (1958), and Suppes (e.g.,

Suppes & Morningstar, 1972), serious analyses of tasks used in school instruction have not played an important part in the recent psychological studies of learning.

Psychological study of school learning may or may not lead to helpful suggestions for improvement in the practice of instruction. However, it seems quite certain that instructional tasks constitute a domain of study and analysis that is potentially productive for psychological theory. Learning tasks in the school curriculum are complex enough to raise non-trivial theoretical questions. At the same time, the nature of the concepts and skills to be acquired nas been shaped by a process of evolution in which materials that cannot be learned by most students and methods of instruction that are patently unsuccessful have been eliminated over the years. Cognitive psychologists can consider school learning tasks as species of learning that have adapted to the constraints of children's cognitive limitations and the normal abilities of teachers and authors of instructional materials. A deep theoretical understanding of the psychological processes involved in school learning could become the keystone of a significant new psychological theory of learning.

Reference Notes

1. de Kleer, J. Qualitative and quantitative knowledge in classical mechanics. Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Technical Report AI-TR-352, December 1975.
2. Heller, J. I., & Greeno, J. G. Semantic processing in arithmetic word problem solving. Paper presented at the meeting of the Midwestern Psychological Association, Chicago, May 1978.
3. Kimble, G. A. Landmarks in the history of learning. Paper presented at the meeting of the American Psychological Association, New York, 1978.
4. Novak, G. S., Jr. Computer understanding of physics problems stated in natural language. University of Texas: Department of Computer Science, Technical Report NL-30, 1976.
5. Riley, M. S., & Greeno, J. G. Importance of semantic structure in the difficulty of arithmetic word problems. Paper presented at the meeting of the Midwestern Psychological Association, Chicago, May 1978.

References

Anderson, J. R. Language, memory, and thought. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1976.

Anderson, J. R., Kline, P. J., & Beasley, C. M. A general learning theory and its application to schema abstraction. In G. H. Bower (Ed.), The psychology of learning and motivation (Vol. 13). New York: Academic Press, 1979.

Anzai, Y., & Simon, H. A. The theory of learning by doing. Psychological Review, 1979, 86, 124-140.

Atkinson, R. C., & Crothers, E. J. A comparison of paired-associate learning models having different acquisition and retention axioms. Journal of Mathematical Psychology, 1964, 1, 285-315.

Atkinson, R. C., & Shiffrin, R. M. Human memory: A proposed system and its control processes. In G. H. Bower & J. T. Spence (Eds.), The psychology of learning and motivation (Vol. 2). New York: Academic Press, 1968.

Atwood, M. E., & Polson, P. G. A process model for water jug problems. Cognitive Psychology, 1976, 8, 191-216.

Bartlett, F. C. Remembering. Cambridge, England: Cambridge University Press, 1932.

Bernbach, H. A. Replication processes in human memory and learning. In G. H. Bower & J. T. Spence (Eds.), The psychology of learning and motivation (Vol. 3). New York: Academic Press, 1969.

Bower, G. H. Application of a model to paired-associate learning. Psychometrika, 1961, 26, 255-280.

Bower, G. H., & Trabasso, T. R. Concept identification. In R. C. Atkinson (Ed.), Studies in mathematical psychology. Stanford: Stanford University Press, 1964.

Brown, J. S., & Burton, R. R. Diagnostic models for procedural bugs in basic mathematical skills. Cognitive Science, 1978, 2, 155-192.

Brownell, W. A. The development of children's number ideas in the primary grades. Chicago: University of Chicago, 1928. (Supplementary Educational Monographs, Number 35, August 1928.)

Bruner, J. S. Toward a theory of instruction. New York: Norton, 1966.

Bruner, J. S., Goodnow, J. J., & Austin, G. A. A study of thinking. New York: Wiley, 1956.

Bush, R. R., & Mosteller, F. Stochastic models for learning. New York: Wiley, 1955.

Craik, F. I. M., & Tulving, E. Depth of processing and the retention of words in episodic memory. Journal of Experimental Psychology: General, 1972, 104, 268-294.

Crowder, R. G. Principles of learning and memory. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1976.

Estes, W. K. Toward a statistical theory of learning. Psychological Review, 1950, 57, 94-107.

Estes, W. K. The statistical approach to learning theory. In S. Koch (Ed.), Psychology: A study of a science (Vol. 2). General systematic formulations, learning, and special processes. New York: McGraw-Hill, 1959.

Estes, W. K. Learning theory and the new "mental chemistry." Psychological Review, 1960, 67, 207-223.

Estes, W. K., & Straughan, J. H. Analysis of a verbal conditioning situation in terms of statistical learning theory. Journal of Experimental Psychology, 1954, 47, 225-234.

Gentner, D. Evidence for the psychological reality of semantic components: The verbs of possession. In D. A. Norman & D. E. Rumelhart, Explorations in cognition. San Francisco: Freeman, 1975.

Gibson, E. J. A systematic application of the concepts of generalization and differentiation to verbal learning. Psychological Review, 1940, 47, 196-229.

Greeno, J. G. Paired-associate learning with short-term retention: Mathematical analysis and data regarding identification of parameters. Journal of Mathematical Psychology, 1967, 4, 430-472.

Greeno, J. G. Indefinite goals in well-structured problems. Psychological Review, 1976, 83, 479-491.

Greeno, J. G. Process of understanding in problem solving. In N. J. Castellan, D. B. Pisoni, & G. R. Potts (Eds.), Cognitive theory (Vol. 2). Hillsdale, N.J.: Lawrence Erlbaum Associates, 1977.

Greeno, J. G. A study of problem solving. In R. Glaser (Ed.), Advances in instructional psychology (Vol. 1). Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978.

Greeno, J. G., & Bjork, R. A. Mathematical learning theory and the new "mental forestry." Annual Review of Psychology, 1973, 24, 81-116.

Greeno, J. G., James, C. T., DaPolito, F. J., & Polson, P. G. Associative learning: A cognitive analysis. Englewood Cliffs, N.J.: Prentice-Hall, 1978.

Guthrie, E. R. The psychology of learning. New York: Harper & Row, 1935.

Hayes, J. R., & Simon, H. A. Understanding written problem instructions. In L. W. Gregg (Ed.), Knowledge and cognition. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1974.

Hull, C. L. Principles of behavior: An introduction to behavior theory. New York: Appleton-Century-Crofts, 1943.

Hull, C. L., Hovland, C. I., Ross, R. T., Hall, M., Perkins, D. T., & Fitch, F. B. Mathematico-deductive theory of rote learning. New Haven, Conn.: Yale University Press, 1940.

Judd, C. H. Psychological analysis of the fundamentals of arithmetic. Chicago: University of Chicago, 1927. (Supplementary Educational Monographs, Number 32, February 1927.)

Kintsch, W., & Morris, C. J. Application of a Markov model to free recall and recognition. Journal of Experimental Psychology, 1965, 69, 200-206.

Kintsch, W., & Vipond, D. Reading comprehension and readability in educational practice and psychological theory. In L. Nilsson (Ed.), Perspectives on memory research. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1979.

Klahr, D., & Wallace, J. G. Cognitive development: An information-processing view. New York: Halstead Press, 1976.

Koch, S. Clark L. Hull. In W. K. Estes, S. Koch, K. MacCorquodale, P. E. Meehl, C. G. Mueller, W. N. Schoenfeld, & W. S. Verplanck, Modern learning theory. New York: Appleton-Century-Crofts, 1954.

Lawrence, D. H. The nature of a stimulus. In S. Koch (Ed.), Psychology: A study of a science (Vol. 5). New York: McGraw-Hill, 1963.

Lehnert, W. G. The process of question answering. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978.

Lovejoy, E. Attention in discrimination learning: A point of view and a theory. San Francisco: Holden-Day, 1968.

Luce, R. D. Individual choice behavior: A theoretical analysis. New York: Wiley, 1959.

Mandler, J. M., & Johnson, N. S. Remembrance of things parsed: Story structure and recall. Cognitive Psychology, 1977, 9, 111-151.

McDermott, J., & Larkin, J. H. Re-representing textbook physics problems. In Proceedings of the Second National Conference, Canadian Society for Computational Studies of Intelligence. University of Toronto, 1978.

Melton, A. W., & Martin, E. (Eds.). Coding processes in human memory. Washington: Winston, 1972.

Newell, A., & Simon, H. A. Human problem solving. Englewood Cliffs, N.J.: Prentice-Hall, 1972.

Norman, D. A., & Rumelhart, D. E. A system for perception and memory. In D. A. Norman (Ed.), Models of human memory. New York: Academic Press, 1970.

Norman, D. A., & Rumelhart, D. E. Explorations in cognition. San Francisco: Freeman, 1975.

Piaget, J. Science of education and the psychology of the child. New York: Orion Press, 1970.

Polson, M. C., Restle, F., & Polson, P. G. Association and discrimination in paired-associates learning. Journal of Experimental Psychology, 1965, 69, 47-55.

Postman, L. One-trial learning. In C. N. Cofer & B. S. Musgrave (Eds.), Verbal behavior and learning: Problems and processes. New York: McGraw-Hill, 1963.

Postman, L., & Underwood, B. J. Critical issues in interference theory. Memory & Cognition, 1973, 1, 19-40.

Restle, F. The selection of strategies in cue learning. Psychological Review, 1962, 69, 329-343.

Restle, F. The significance of all-or-none learning. Psychological Bulletin, 1965, 62, 313-324.

Restle, F., & Greeno, J. G. Introduction to mathematical psychology. Reading, Mass.: Addison-Wesley, 1970.

Rock, I. The role of repetition in associative learning. American Journal of Psychology, 1957, 70, 186-193.

Rundus, D., & Atkinson, R. C. Rehearsal processes in free recall: A procedure for direct observation. Journal of Verbal Learning and Verbal Behavior, 1970, _, 99-105.

Sacerdoti, E. D. A structure for plans and behavior. New York: Elsevier, 1977.

Schank, R. C., & Abelson, R. P. Scripts, plans, goals, and understanding: An inquiry into human knowledge structures. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1977.

Simon, D. P., & Simon, H. A. Individual differences in solving physics problems. In R. Siegler (Ed.), Children's thinking: What develops? Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978.

Simon, H. A. The functional equivalence of problem solving skills. Cognitive Psychology, 1975, 7, 268-288.

Skinner, B. F. The behavior of organisms: An experimental analysis. New York: Appleton-Century-Crofts, 1938.

Skinner, B. F. Teaching machines. Science, 1958, 128, 969-977.

Spence, K. W. Behavior theory and conditioning. New Haven, Conn.: Yale University Press, 1956.

Suppes, P., & Morningstar, M. Computer-assisted instruction at Stanford, 1966-1968. New York: Academic Press, 1972.

Thorndike, E. L. The psychology of arithmetic. New York: MacMillan, 1922.

Thurstone, L. L. The learning curve equation. Psychological Review Monograph Supplement, 1919, 26, No. 3, 1-51 pp.

Thurstone, L. L. The learning function. Journal of General Psychology, 1930, 3, 469-491.

Tolman, E. C. Purposive behavior in animals and men. New York: Century, 1932.

Underwood, B. J. An evaluation of the Gibson theory of verbal learning. In C. Cofer (Ed.), Verbal learning and verbal behavior. New York: McGraw-Hill, 1961.

Underwood, B. J. The representativeness of rote verbal learning. In A. W. Melton (Ed.), Categories of human learning. New York: Academic Press, 1964.

Winograd, T. Understanding natural language. Cognitive Psychology, 1972, 3, 1-191.

Woodward, A. E., Bjork, R. A., & Jongeward, R. H. Recall and recognition as a function of primary rehearsal. Journal of Verbal Learning and Verbal Behavior, 1973, 12, 608-617.

Woodworth, R. S. Experimental psychology. New York: Holt, 1938.

Footnotes

This paper is dedicated to the memory of Arthur W. Melton.

Work on this paper was supported by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-78-C-0022, Contract Authority Identification Number, NR 157-408. Also supported by the Learning Research and Development Center, supported in part as a research and development center by funds from the National Institute of Education (NIE), United States Department of Health, Education, and Welfare.

The paper originated as the author's Presidential Address at the Midwestern Psychological Association meeting, Chicago, Illinois, May, 1978.

Navy

1 Dr. Robert Breaux
Code N-711
NAVTRAEQUIPCEN
Orlando, FL 32813

1 Dr. Richard Elster
Department of Administrative Sciences
Naval Postgraduate School
Monterey, CA 93940

1 DR. PAT FEDERICO
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

1 Dr. John Ford
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Richard Gibson
Bureau of medicine and surgery
Code 3C13
Navy Department
Washington, DC 20372

1 LT Steven D. Harris, MSC, USN
Code 6021
Naval Air Development Center
Warminster, Pennsylvania 18974

1 Dr. Patrick R. Harrison
Psychology Course Director
LEADERSHIP & LAW DEPT. (7b)
DIV. OF PROFESSIONAL DEVELOPMMENT
U.S. NAVAL ACADEMY
ANNAPOLIS, MD 21402

1 LCDR Wade Helm
Psychology Department
University of South Dakota
Vermillion, SD 57069

1 CDR Charles W. Hutchins
Naval Air Systems Command Hq
AIR-340F
Navy Department
Washington, DC 20361

Navy

1 CDR Robert S. Kennedy
Head, Human Performance Sciences
Naval Aerospace Medical Research Lab
Box 29407
New Orleans, LA 70189

1 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

1 Dr. Leonard Kroeker
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. James McBride
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. George Moeller
Head, Human Factors Dept.
Naval Submarine Medical Research Lab
Groton, CN 06340

1 Dr William Montague
Navy Personnel R&D Center
San Diego, CA 92152

1 Commanding Officer
U.S. Naval Amphibious School
Coronado, CA 92155

1 Library
Naval Health Research Center
P. O. Box 85122
San Diego, CA 92138

1 Naval Medical R&D Command
Code 44
National Naval Medical Center
Bethesda, MD 20014

1 Ted M. I. Yellen
Technical Information Office, Code 201
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

Navy

1 Library, Code P201L
Navy Personnel R&D Center
San Diego, CA 92152

5 Technical Director
Navy Personnel R&D Center
San Diego, CA 92152

1 Director, Navy Personnel R&D Center
Washington Liason Office
Building 200, 2N
Washington Navy Yard, DC 20374

6 Commanding Officer
Naval Research Laboratory
Code 2627
Washington, DC 20390

1 Psychologist
ONR Branch Office
Bldg 114, Section D
666 Summer Street
Boston, MA 02210

1 Psychologist
ONR Branch Office
536 S. Clark Street
Chicago, IL 60605

1 Office of Naval Research
Code 441
800 N. Quincy Street
Arlington, VA 22217

5 Personnel & Training Research Programs
(Code 458)
Office of Naval Research
Arlington, VA 22217

1 Psychologist
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101

1 Captain Donald F. Parker, USN
Commanding Officer
Navy Personnel R&D Center
San Diego, CA 92152

Navy

1 LT Frank C. Petho, MSC, USN (Ph.D)
Code L51
Naval Aerospace Medical Research Laborat
Pensacola, FL 32508

1 Roger W. Remington, Ph.D
Code L52
NAMRL
Pensacola, FL 32508

1 Dr. Bernard Rimland (03B)
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Ronald Weitzman
Code 54 WZ
Department of Administrative Sciences
U. S. Naval Postgraduate School
Monterey, CA 93940

1 Dr. Robert Wisher
Code 309
Navy Personnel R&D Center
San Diego, CA 92152

1 DR. MARTIN F. WISKOFF
NAVY PERSONNEL R& D CENTER
SAN DIEGO, CA 92152

Army

1 Technical Director
U. S. Army Research Institute for the Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 HQ USAREUE & 7th Army
ODCSOPS
USAAREUE Director of GED
APO New York 09403

1 DR. RALPH DUSEK
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Dr. Beatrice J. Farr
Army Research Institute (PERI-OK)
5001 Eisenhower Avenue
Alexandria, VA 22333

1 DR. FRANK J. HARRIS
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Dr. Ed Johnson
Army Research Institute
5001 Eisenhower Blvd.
Alexandria, VA 22333

1 Dr. Michael Kaplan
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Dr. Milton S. Katz
Training Technical Area
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Director
U.S. Army Human Engineering Labs
Attn: DRXHE-DB
Aberdeen Proving Ground, MD 21005

Army

1 Dr. Harold F. O'Neil, Jr.
Attn: PERI-OK
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Robert Sasmor
U. S. Army Research Institute for the Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Frederick Steinheiser
U. S. Army Reserch Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Air Force

1 U.S. Air Force Office of Scientific Research
Life Sciences Directorate, NL
Bolling Air Force Base
Washington, DC 20332

1 Dr. Earl A. Alluisi
HQ, AFHRL (AFSC)
Brooks AFB, TX 78235

1 Dr. Philip De Leo
AFHRL/TT
Lowry AFB, CO 80230

1 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AFOSR
Bolling AFB, DC 20332

1 Dr. Ronald G. Hughes
AFHRL/OTR
Williams AFB, AZ 85224

1 Dr. Malcolm Ree
AFHRL/MP
Brooks AFB, TX 78235

1 Dr. Marty Rockway (AFHRL/TT)
Lowry AFB
Colorado 80230

1 Dr. Frank Schufletowski
U.S. Air Force
ATC/XPTD
Randolph AFB, TX 78148

2 3700 TCHTW/TTGH Stop 32
Sheppard AFB, TX 76311

1 Jack A. Thorpe, Maj., USAF
Naval War College
Providence, RI 02846

1 Brian K. Waters, Lt Col, USAF
Air War College (EDV)
Maxwell AFB, AL 36112

Marines

1 H. William Greenup
Education Advisor (E031)
Education Center, MCDEC
Quantico, VA 22134

1 Headquarters, U. S. Marine Corps
Code MPI-20
Washington, DC 20380

1 Special Assistant for Marine Corps Matters
Code 100M
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

1 DR. A.L. SLAFKOSKY
SCIENTIFIC ADVISOR (CODE RD-1)
HQ, U.S. MARINE CORPS
WASHINGTON, DC 20380

CoastGuard

1 Mr. Thomas A. Warm
U. S. Coast Guard Institute
P. O. Substation 18
Oklahoma City, OK 73169

Other DoD

12 Defense Documentation Center
Cameron Station, Bldg. 5
Alexandria, VA 22314
Attn: TC

1 Dr. Craig I. Fields
Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

1 Dr. Dexter Fletcher
ADVANCED RESEARCH PROJECTS AGENCY
1400 WILSON BLVD.
ARLINGTON, VA 22209

1 Military Assistant for Training and
Personnel Technology
Office of the Under Secretary of Defense
for Research & Engineering
Room 3D129, The Pentagon
Washington, DC 20301

1 HEAD, SECTION ON MEDICAL EDUCATION
UNIFORMED SERVICES UNIV. OF THE
HEALTH SCIENCES
6917 ARLINGTON ROAD
BETHESDA, MD 20014

Civil Govt

1 Dr. Susan Chipman
Learning and Development
National Institute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Joseph I. Lipson
SEDR W-638
National Science Foundation
Washington, DC 20550

1 William J. McLaurin
Rm. 301, Internal Revenue Service
2221 Jefferson Davis Highway
Arlington, VA 22202

1 Dr. H. Wallace Sinaiko
Program Director
Manpower Research and Advisory Services
Smithsonian Institution
801 North Pitt Street
Alexandria, VA 22314

1 Robert W. Stump
Home Community & Work Group
Mail Stop 4
National Institute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Frank Withrow
U. S. Office of Education
400 Maryland Ave. SW
Washington, DC 20202

1 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, DC 20550

Non Govt

1 Dr. John R. Anderson
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Anderson, Thomas H., Ph.D.
Center for the Study of Reading
174 Children's Research Center
51 Gerty Drive
Champiagn, IL 61820

1 Dr. John Annett
Department of Psychology
University of Warwick
Coventry CV4 7AL
ENGLAND

1 DR. MICHAEL ATWOOD
SCIENCE APPLICATIONS INSTITUTE
40 DENVER TECH. CENTER WEST
7935 E. PRENTICE AVENUE
ENGLEWOOD, CO 80110

1 1 psychological research unit
Dept. of Defense (Army Office)
Campbell Park Offices
Canberra ACT 2600, Australia

1 Dr. Alan Baddeley
Medical Research Council
Applied Psychology Unit
15 Chaucer Road
Cambridge CB2 2EF
ENGLAND

1 Dr. Patricia Baggett
Department of Psychology
University of Denver
University Park
Denver, CO 80208

1 Mr Avron Barr
Department of Computer Science
Stanford University
Stanford, CA 94305

Non Govt

1 Dr. Jackson Beatty
Department of Psychology
University of California
Los Angeles, CA 90024

1 Dr. John Bergan
School of Education
University of Arizona
Tuscon AZ 85721

1 DezWPs im Streitkraefteamt
Postfach 20 50 03
D-5300 Bonn 2
WEST GERMANY

1 Dr. Nicholas A. Bond
Dept. of Psychology
Sacramento State College
600 Jay Street
Sacramento, CA 95819

1 Dr. Lyle Bourne
Department of Psychology
University of Colorado
Boulder, CO 80309

1 Dr. Robert Brennan
American College Testing Programs
P. O. Box 168
Iowa City, IA 52240

1 Dr. John S. Brown
XEROX Palo Alto Research Center
3333 Coyote Road
Palo Alto, CA 94304

1 Dr. John B. Carroll
Psychometric Lab
Univ. of No. Carolina
Davie Hall 013A
Chapel Hill, NC 27514

1 Charles Myers Library
Livingstone House
Livingstone Road
Stratford
London E15 2LJ
ENGLAND

Non Govt

1 Dr. William Chase
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Micheline Chi
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. William Clancey
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. Kenneth E. Clark
College of Arts & Sciences
University of Rochester
River Campus Station
Rochester, NY 14627

1 Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, Ma 02138

1 Dr. Meredith P. Crawford
American Psychological Association
1200 17th Street, N.W.
Washington, DC 20036

1 Dr. Hans Crombag
Education Research Center
University of Leyden
Boerhaavelaan 2
2334 EN Leyden
The NETHERLANDS

1 Dr. Kenneth B. Cross
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

1 Dr. Fred Reif
SESAME
c/o Physics Department
University of California
Berkeley, CA 94720

Non Govt

1 Director
Behavioural Sciences Division
Defence & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsview, Ontario M3M 3B9
CANADA

1 Dr. Emmanuel Donchin
Department of Psychology
University of Illinois
Champaign, IL 61820

1 Dr. Hubert Dreyfus
Department of Philosophy
University of California
Berkely, CA 94720

1 LCOL J. C. Eggenberger
DIRECTORATE OF PERSONNEL APPLIED RESEARC
NATIONAL DEFENCE HQ
101 COLONEL BY DRIVE
OTTAWA, CANADA K1A OK2

1 ERIC Facility-Acquisitions
4833 Rugby Avenue
Bethesda, MD 20014

1 Dr. Ed Feigenbaum
Department of Computer Science
Stanford University
Stanford, CA 94305

1 Dr. Richard L. Ferguson
The American College Testing Program
P.O. Box 168
Iowa City, IA 52240

1 Mr. Wallace Feurzeig
Bolt Beranek & Newman, Inc.
50 Moulton St.
Cambridge, MA 02138

1 Univ. Prof. Dr. Gerhard Fischer
Liebiggasse 5/3
A 1010 Vienna
AUSTRIA

Non Govt

1 Dr. Edwin A. Fleishman
Advanced Research Resources Organ.
Suite 900
4330 East West Highway
Washington, DC 20014

1 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

1 Dr. Alinda Friedman
Department of Psychology
University of Alberta
Edmonton, Alberta
CANADA T6G 2E9

1 Dr. R. Edward Geiselman
Department of Psychology
University of California
Los Angeles, CA 90024

1 DR. ROBERT GLASER
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 Dr. Marvin D. Glock
217 Stone Hall
Cornell University
Ithaca, NY 14853

1 Dr. Daniel Gopher
Industrial & Management Engineering
Technion-Israel Institute of Technology
Haifa
ISRAEL

1 Dr. Harold Hawkins
Department of Psychology
University of Oregon
Eugene OR 97403

1 Dr. Barbara Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

Non Govt

1 Dr. Frederick Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. James R. Hoffman
Department of Psychology
University of Delaware
Newark, DE 19711

1 Dr. Lloyd Humphreys
Department of Psychology
University of Illinois
Champaign, IL 61820

1 Library
HumRRO/Western Division
27857 Berwick Drive
Carmel, CA 93921

1 Dr. Earl Hunt
Dept. of Psychology
University of Washington
Seattle, WA 98105

3 Journal Supplement Abstract Service
American Psychological Association
1200 17th Street N.W.
Washington, DC 20036

1 Dr. Steven W. Keele
Dept. of Psychology
University of Oregon
Eugene, OR 97403

1 Dr. Walter Kintsch
Department of Psychology
University of Colorado
Boulder, CO 80302

1 Dr. David Kieras
Department of Psychology
University of Arizona
Tuscon, AZ 85721

Non Govt

1 Dr. Stephen Kosslyn
Harvard University
Department of Psychology
33 Kirkland Street
Cambridge, MA 02138

1 Dr. Jill Larkin
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

1 Dr. Alan Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

1 Dr. Michael Levine
210 Education Building
University of Illinois
Champaign, IL 61820

1 Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat
Groningen
NETHERLANDS

1 Dr. Mark Miller
Computer Science Laboratory
Texas Instruments, Inc.
Mail Station 371, P.O. Box 225936
Dallas, TX 75265

1 Dr. Allen Munro
Behavioral Technology Laboratories
1845 Elena Ave., Fourth Floor
Redondo Beach, CA 90277

1 Dr. Donald A Norman
Dept. of Psychology C-009
Univ. of California, San Diego
La Jolla, CA 92093

1 Dr. Melvin R. Novick
356 Lindquist Center for Measurment
University of Iowa
Iowa City, IA 52242

Non Govt

1 Dr. Seymour A. Papert
Massachusetts Institute of Technology
Artificial Intelligence Lab
545 Technology Square
Cambridge, MA 02139

1 Dr. James A. Paulson
Portland State University
P.O. Box 751
Portland, OR 97207

1 MR. LUIGI PETRULLO
2431 N. EDGEWOOD STREET
ARLINGTON, VA 22207

1 Dr. Martha Polson
Department of Psychology
University of Colorado
Boulder, CO 80302

1 DR. PETER POLSON
DEPT. OF PSYCHOLOGY
UNIVERSITY OF COLORADO
BOULDER, CO 80309

1 DR. DIANE M. RAMSEY-KLEE
R-K RESEARCH & SYSTEM DESIGN
3947 RIDGEMONT DRIVE
MALIBU, CA 90265

1 MINRAT M. L. RAUCH
P II 4
BUNDESMINISTERIUM DER VERTEIDIGUNG
POSTFACH 1328
D-53 BONN 1, GERMANY

1 Dr. Mark D. Reckase
Educational Psychology Dept.
University of Missouri-Columbia
4 Hill Hall
Columbia, MO 65211

1 Dr. Fred Reif
SESAME
c/o Physics Department
University of California
Berkely, CA 94720

Non Govt

1 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson St. NW
Washington, DC 20007

1 Dr. Ernst Z. Rothkopf
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

1 PROF. FUMIKO SAMEJIMA
DEPT. OF PSYCHOLOGY
UNIVERSITY OF TENNESSEE
KNOXVILLE, TN 37916

1 Dr. Irwin Sarason
Department of Psychology
University of Washington
Seattle, WA 98195

1 DR. WALTER SCHNEIDER
DEPT. OF PSYCHOLOGY
UNIVERSITY OF ILLINOIS
CHAMPAIGN, IL 61820

1 Dr. Alan Schoenfeld
Department of Mathematics
Hamilton College
Clinton, NY 13323

1 DR. ROBERT J. SEIDEL
INSTRUCTIONAL TECHNOLOGY GROUP
HUMRRO
300 N. WASHINGTON ST.
ALEXANDRIA, VA 22314

1 Committee on Cognitive Research
% Dr. Lonnie R. Sherrod
Social Science Research Council
605 Third Avenue
New York, NY 10016

1 Dr. Robert Smith
Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

Non Govt

1 Dr. Richard Snow
School of Education
Stanford University
Stanford, CA 94305

1 Dr. Kathryn T. Spoehr
Department of Psychology
Brown University
Providence, RI 02912

1 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 DR. ALBERT STEVENS
BOLT BERANEK & NEWMAN, INC.
50 MOULTON STREET
CAMBRIDGE, MA 02138

1 Dr. David Stone
ED 236
SUNY, Albany
Albany, NY 12222

1 DR. PATRICK SUPPES
INSTITUTE FOR MATHEMATICAL STUDIES IN
THE SOCIAL SCIENCES
STANFORD UNIVERSITY
STANFORD, CA 94305

1 Dr. Hariharan Swaminathan
Laboratory of Psychometric and
Evaluation Research
School of Education
University of Massachusetts
Amherst, MA 01003

1 Dr. Brad Sympson
Psychometric Research Group
Educational Testing Service
Princeton, NJ 08541

Non Govt

1 Dr. Kikumi Tatsuoka
Computer Based Education Research
Laboratory
252 Engineering Research Laboratory
University of Illinois
Urbana, IL 61801

1 Dr. David Thissen
Department of Psychology
University of Kansas
Lawrence, KS 66044

1 Dr. John Thomas
IBM Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

1 DR. PERRY THORNDYKE
THE RAND CORPORATION
1700 MAIN STREET
SANTA MONICA, CA 90406

1 Dr. Douglas Towne
Univ. of So. California
Behavioral Technology Labs
1845 S. Elena Ave.
Redondo Beach, CA 90277

1 Dr. J. Uhlaner
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

1 Dr. Benton J. Underwood
Dept. of Psychology
Northwestern University
Evanston, IL 60201

1 Dr. William R. Uttal
University of Michigan
Institute for Social Research
Ann Arbor, MI 48106

1 Dr. Howard Wainer
Bureau of Social SCience Research
1990 M Street, N. W.
Washington, DC 20036

Non Govt

1 DR. THOMAS WALLSTEN
PSYCHOMETRIC LABORATORY
DAVIE HALL 013A
UNIVERSITY OF NORTH CAROL
CHAPEL HILL, NC 27514

1 Dr. Phyllis Weaver
Graduate School of Education
Harvard University
200 Larsen Hall, Appian Way
Cambridge, MA 02138

1 Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

1 DR. GERSHON WELTMAN
PERCEPTRONICS INC.
6271 VARIEL AVE.
WOODLAND HILLS, CA 91367

1 Dr. Keith T. Wescourt
Information Sciences Dept.
The Rand Corporation
1700 Main St.
Santa Monica, CA 90406

1 DR. SUSAN E. WHITELY
PSYCHOLOGY DEPARTMENT
UNIVERSITY OF KANSAS
LAWRENCE, KANSAS 66044

1 Dr. Christopher Wickens
Department of Psychology
University of Illinois
Champaign, IL 61820

1 Dr. J. Arthur Woodward
Department of Psychology
University of California